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Effect of energy loss on azimuthal correlation of charm and correlated charm decay in collision of lead nuclei at $\sqrt{s}$= 2.76 A TeV

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Abstract. We present the effect of energy loss of charm/anti-charm produced in a relativistic heavy ion collision as they traverse the resulting quark gluon plasma on the azimuthal correlation of $c\bar{c}$ and $D\overline{D}$ pairs and correlated decay of charm into leptons. We employ an empirical model of energy loss by charm quark energy loss and find that the consequences are easily discernible as different cuts on their momenta are applied. We also notice a modest increase in the invariant mass spectrum of dileptons from correlated decay as mentioned above due to energy loss.

Key-words: Charm quark, D mesons, non-photonic electrons, QGP, relativistic heavy ion collisions, NLO-pQCD, correlations

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1. Introduction

Heavy quarks are emerging as valuable probes for the study of quark gluon plasma produced in relativistic heavy ion collision. This has its origin in the large mass of heavy quarks which lends them quite a few advantages, viz, they are produced at a time $\approx \frac{1}{2m_Q}$ which is smaller than the formation time of quark gluon plasma. Their large mass ensures that their production can be calculated reliably using perturbative QCD and they may not be deflected substantially from their path due to collisions with quarks and gluons and due to radiation of gluons. The drag experienced by the heavy quarks due to these collisions and radiations however leads to medium modification of their production which is quite similar to those for light quarks, as leading particles [1, 2]. Recent calculations which treat the so called 'dead cone' with more care [3], also show that heavy quarks lose energy in a manner quite similar to light quarks [4].

Recently it has been pointed out that correlations of heavy quarks (charm and anti-charm) can add a richness to these studies by adding several features [5]. Consider for example heavy quark production at lowest order of pQCD. They would be produced back to back. The two members of the correlated pair may in general lose different amounts of energy as they may cover differing path lengths in the plasma. However if they do not change their directions, they would continue to remain back-to-back. Now consider that there is a strong flow and that the heavy quarks take part in flow [6]. It is now possible that one of them is produced with a transverse momentum parallel to flow velocity and its momentum will increase, while the momentum of the other will decrease. In fact if the radial flow velocity $v_T > p_T/E(\text{charm})$, the charm will change its direction and the back-to-back correlation may change to forward correlations. When, however, the flow velocity is not collinear with the momentum, the final momenta will be separated by $0 < \phi < \pi$. Thus while the energy loss is not likely to alter the angular correlation of heavy quarks at lowest order in pQCD, a strong elliptic flow will bring in some interesting and rich structure, the analysis of which could throw some light on interplay of energy loss and flow.

There is, however, a substantial production of heavy quarks at next to leading order in pQCD. The NLO process $gg \rightarrow Q\overline{Q}$ can proceed in two ways(among others). Either one of the final state gluons in the process $gg \rightarrow gg$ splits ($g \rightarrow Q\overline{Q}$) or one of the heavy quarks radiates a gluon following $gg \rightarrow Q\overline{Q}$. The pair is expected to be collinear in the first case and deviate back-to-back in the second case. The processes where gluon is emitted from the external legs will fill up the region $0 < \phi < \pi$. Now energy loss will alter the correlations in a complex manner. If our assumption on heavy quarks not changing direction due to energy loss largely holds then p_T integrated correlation is likely to remain unchanged. However if we now study the correlation for different cuts on p_T, some interesting patterns may emerge. Different heavy quarks lose different momenta!

We can now discuss correlated decay of charm-anti-charm into electron-positron pair. The invariant pair mass distribution of electron pair obtained from decay shows

interesting features. It is seen earlier that large suppression of heavy quark as seen through R_{AA}, results in increase of D mesons as well as single electron spectrum at low momentum by a few percent. This characteristic increase is quite different from enhancement due to Cronin effect [7] and is found to be due to large effective drag upon charm by thermalized medium. The invariant pair mass distribution of electron pair obtained from decay shows similar feature from effects due to energy loss by charm quarks [8]. The electron pairs pile up at low invariant mass region resulting in characteristic enhancement in electron distribution.

In the following we study some of these features of the correlation of heavy quarks with collision of lead nuclei at 2760 GeV/nucleon as an example. The paper is organized as follows. Sec. 2 contains formalism for charm production cross-section from pp collisions and lead on lead collision at LHC energy. Sec. 3 contains an empirical model of energy loss employed to determine the medium effect on charm correlation. Sec. 4 presents our results and discussions on azimuthal correlation and correlated charm decay. Finally Sec. 5 gives the summary followed by acknowledgement and bibliography.

2. Formulation

The correlation of heavy quarks produced in pp collisions is defined as

$$E_1\, E_2\, \frac{d\sigma}{d^3p_1\, d^3p_2} = \frac{d\sigma}{dy_1\, dy_2\, d^2p_{T1}\, d^2p_{T2}} = C\,, \tag{1}$$

where y_1 and y_2 are the rapidities of heavy quark and anti-quark and $\mathbf{p_{Ti}}$ are the respective momenta.

At the leading order, the differential cross-section for the charm correlation for proton on proton collision is given by

$$C_{LO} = \frac{d\sigma}{dy_1\, dy_2\, d^2p_T}\delta(\mathbf{p_{T1}} + \mathbf{p_{T2}}) \tag{2}$$

One can now calculate [5, 9]

$$\begin{aligned}\frac{d\sigma_{pp}}{dy_1 dy_2 d^2p_T} = 2x_a x_b \sum_{ij} \Bigg[& f_i^{(a)}(x_a, Q^2) f_j^{(b)}(x_b, Q^2) \frac{d\hat{\sigma}_{ij}(\hat{s}, \hat{t}, \hat{u})}{d\hat{t}} \\ + \; & f_j^{(a)}(x_a, Q^2) f_i^{(b)}(x_b, Q^2) \frac{d\hat{\sigma}_{ij}(\hat{s}, \hat{u}, \hat{t})}{d\hat{t}} \Bigg] / (1 + \delta_{ij})\;,\end{aligned} \tag{3}$$

where p_T and $y_{1,2}$ are the momenta and rapidities of produced charm and anti-charm and x_a and x_b are the fractions of the momenta carried by the partons from their interacting parent hadrons. These are given by

$$x_a = \frac{M_T}{\sqrt{s}}(e^{y_1} + e^{y_2})\;; \quad x_b = \frac{M_T}{\sqrt{s}}(e^{-y_1} + e^{-y_2})\;. \tag{4}$$

where M_T $(= \sqrt{m_Q^2 + p_T^2})$, is the transverse mass of the produced heavy quark. The subscripts i and j denote the interacting partons, and $f_{i/j}$ are the partonic distribution

functions for the nucleons. The invariant amplitude, $|M|^2$ in differential cross-section $d\hat{\sigma}/d\hat{t}$ is taken from ref. [10].

The processes included for LO calculations are:

$$g + g \rightarrow c + \overline{c}$$
$$q + \bar{q} \rightarrow c + \overline{c}\ . \qquad (5)$$

At Next-to-Leading order the subprocesses included are as follows:

$$g + g \rightarrow c + \overline{c} + g$$
$$q + \bar{q} \rightarrow c + \overline{c} + g$$
$$g + q(\bar{q}) \rightarrow c + \overline{c} + q(\bar{q})\ . \qquad (6)$$

The eq. 1 gives the correlation of heavy quarks from initial fusion in proton-proton collision. The azimuthal correlation of heavy quark for Pb+Pb collision at given impact parameter is given by

$$E_c\, E_{\bar{c}}\, \frac{dN_{AA}}{d^3p_c\, d^3p_{\bar{c}}} = T_{AA} E_c\, E_{\bar{c}}\, \frac{d\sigma_{pp}}{d^3p_c\, d^3p_{\bar{c}}} \qquad (7)$$

For lead on lead collisions at LHC, we have used T_{AA} = 292 fm^{-2} for b = 0 fm We have used CTEQ5M structure function. The factorization, renormalization, and fragmentation scales are chosen as $2\sqrt{m_c^2 + p_T^2}$ and the charm quark mass, m_c has been taken as 1.5 GeV.

3. Energy Loss Formalism

We use the empirical model for the energy loss for charm quarks proposed in one of our earlier paper. We perform a Monte Carlo implementation of our model calculations and estimate the azimuthal correlation as well as correlated decay of charm pair with charm cross-section determined using NLO-pQCD calculations.

We assume that the energy loss of heavy quarks proceeds through the momentum loss per collision is given by, [11]

$$(\Delta p)_i = \alpha\, (p_i)^\beta\ , \qquad (8)$$

so that one can write

$$\frac{dp}{dx} = -\frac{\Delta p}{\lambda} \qquad (9)$$

where α and β are parameters with best values at $\sqrt{s}$= 2760 GeV/nucleon taken from publication by Younus et al [1] and λ is the mean free path of the charm quark, taken as 1 fm throughout. Thus the momentum of the charm quark after n collisions will be given by

$$p_{n+1} = p_n - (\Delta p)_n \qquad (10)$$

The probability for the charm quark to have n collisions, while covering the path length L is given by

$$P(n,L) = \frac{(L/\lambda)^n}{n!} e^{-L/\lambda}. \tag{11}$$

So now we estimate the largest number of collisions- N, which the charm quark having momentum p_T can undergo. Next we sample the number of collisions n, which the charm undergoes from the distribution

$$p(n) = P(n,L)/\sum_{n=1}^{N} P(n,L) \tag{12}$$

to get the final momentum of the charm(anti-charm) quark.

Next we fragment the charm quark using Peterson fragmentation function given by D. We have assumed that $D(z)$, where $z = p_D/p_c$, is identical for all the D-mesons, [12] and

$$D_D^{(c)}(z) = \frac{n_D}{z[1 - 1/z - \epsilon_p/(1-z)]^2} \ , \tag{13}$$

where ϵ_p is the Peterson parameter and

$$\int_0^1 dz\, D(z) = 1 \ . \tag{14}$$

We have kept it fixed at ϵ_p=0.13.

Then we have included semileptonic decay of $D(\overline{D})$ mesons by parameterizing electron distribution function taken from Ref. [13]. Finally we show our results for $dN_{c\overline{c}}/d\Delta\phi$, $dN_{D\bar{D}}/d\Delta\phi$, $E_c\, E_{\overline{c}} dN/d^3p_c d^3p_{\overline{c}}$ and $dN/dM_{e^+e^-}$.

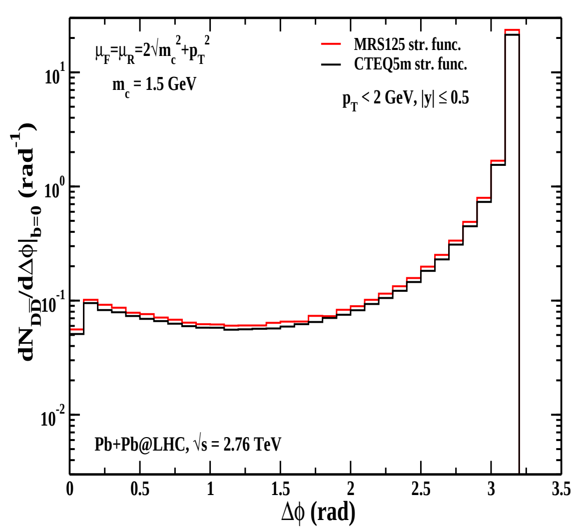

Figure 1. (colour on-line)Comparison of D mesons azimuthal spectrum for two different structure functions.

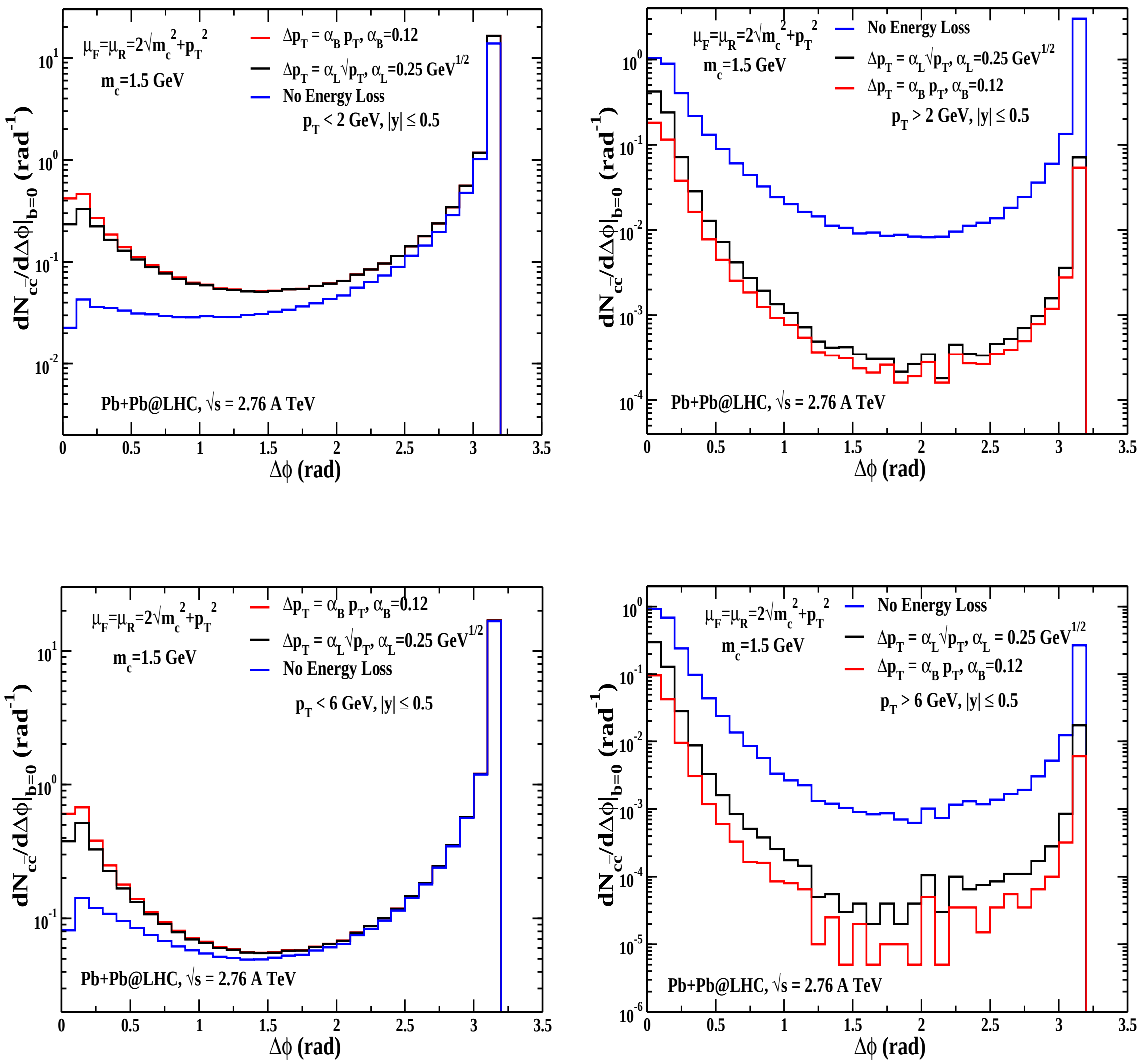

Figure 2. (Colour on-line)$dN/d\Delta\phi$ vs $\Delta\phi$ of $c\bar{c}$ pair for (upper left)p_T < 2.0 GeV, (upper right)p_T > 2.0 GeV. (lower left)p_T < 6.0 GeV, (lower right)p_T > 6.0 GeV.

4. Results and Discussions

We have used NLO-MNR code [14] with CTEQ5M structure function for estimating charm cross-section for all leading and next-to-leading pQCD processes. The scaling factor used is $2\sqrt{m_c^2 + p_T^2}$ with m_c=1.5 GeV. In this paper we have used two different values for parameter 'β'=1.0 for B-H type and β=0.5 for LPM type of energy loss mechanisms respectively. Correspondingly α = 0.12 for B-H type and 0.25 GeV$^{1/2}$ for LPM type are taken as the best values at $\sqrt{s}$ = 2760 GeV/nucleon. The entire calculation is done for central collision (b=0fm) and for mid rapidity, -0.5$\leq$y$\leq$0.5

To check the consistency in our results we use two different partonic structure functions one of which is CTEQ5M and other an old one MRS125. The comparison

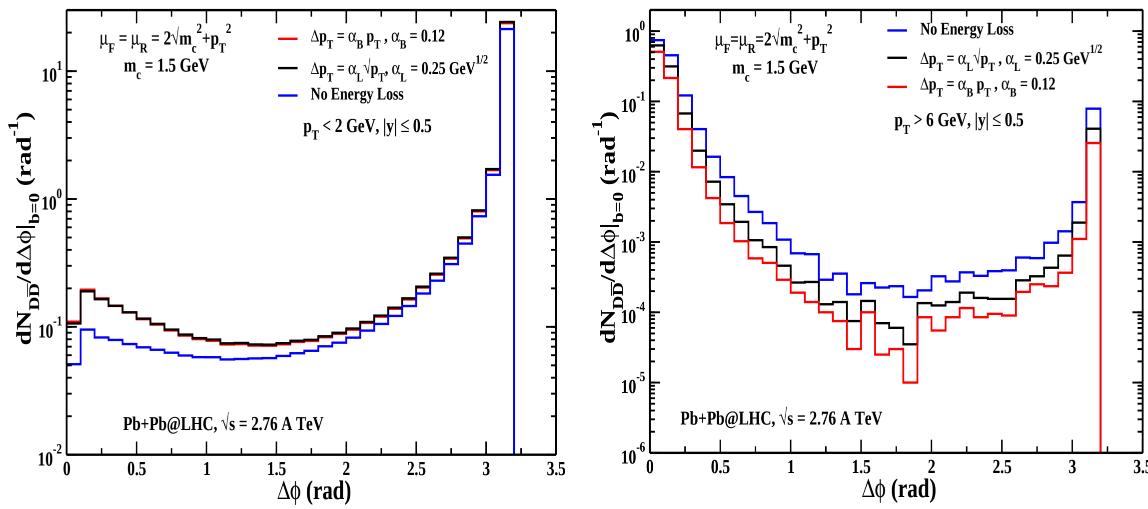

Figure 3. (Colour on-line)same as Fig.2, $dN/d\Delta\phi$ vs $\Delta\phi$ of $D\overline{D}$ pair for (left)$p_T <$ 2.0 GeV, (right)$p_T >$ 6.0 GeV.

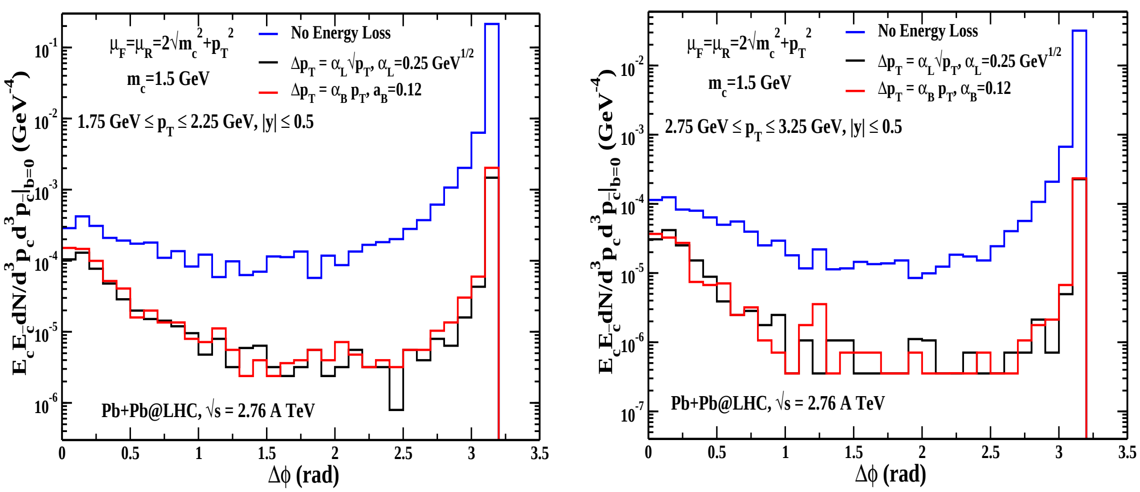

Figure 4. (Colour on-line)Azimuhtal correlation of $c\overline{c}$ pair for (left) $< p_T >$=2.0 GeV, (right) $< p_T >$=3.0 GeV

is shown in Fig. 1, where the difference in the two distributions is very small and the shape almost identical. However more recent structure functions like CTEQ6M and CTEQ6.6 etc. must be used in order to have more up-to-date results. These issues will be addressed in our next publication on heavy quark correlation.

Next let us recall that LO contribution can be differentiated from NLO contribution with different p_T cuts on charm momentum. Leading order processes give back to back charm pairs which are entirely visible around $\Delta\phi$=π while NLO contribution is distributed from $\Delta\phi$=$0-\pi$.

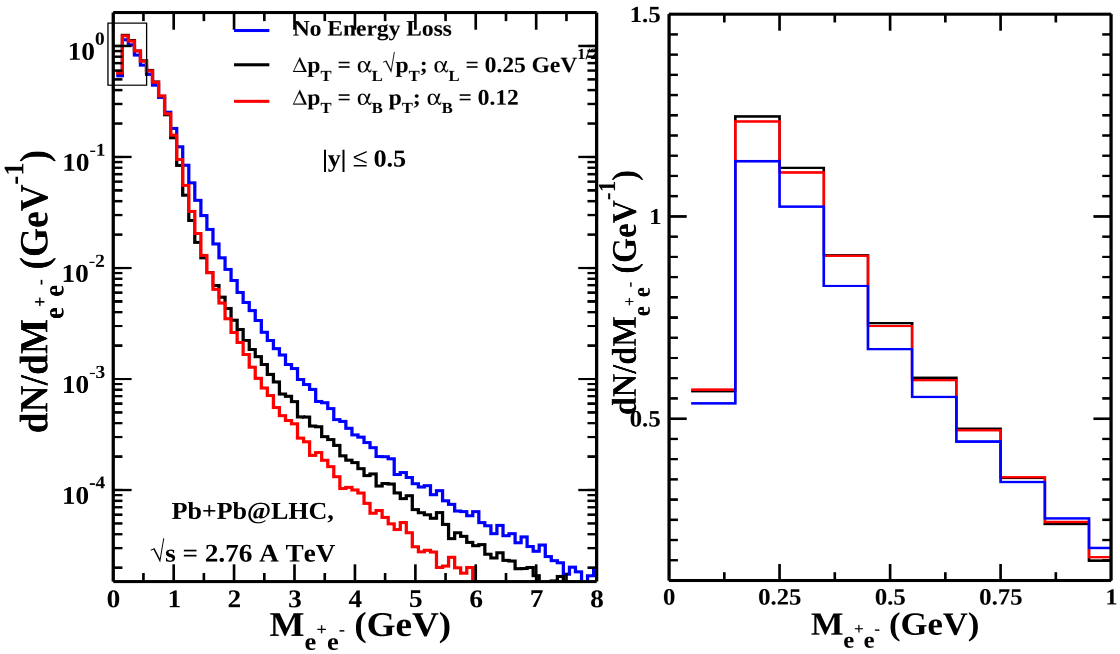

Figure 5. (Colour on-line)Invariant mass distribution for di-electron (inset)Increase in di-electron spectrum for $M_{e^+e^-}$ <1.0 GeV, shown in linear scale.

In Fig. 2, we show our results for $dN_{c\bar{c}}/d\phi$ for different p_T cuts. Realizing that all heavy quarks now appear with reduced momenta, we see that if we look at $p_T < 2$ GeV or $p_T < 6$ GeV, then the back-to-back correlation rise by up to a factor of 10 for $\phi = 0$. The results for $p_T > 2$ GeV or $p_T > 6$ GeV are more dramatic in that the ϕ=π correlation now reduces by more than a factor of 10 while that for ϕ=0 decreases from its value for no energy loss.

We show $dN_{D\bar{D}}/d\Delta\phi$ for $p_T > 6.0$ GeV and $p_T < 2.0$ GeV in Fig. 3. Comparing it with Fig. 2 for same p_T regions, we observe certain differences which we now discuss. For $p_T < 2.0$ GeV, we observe that D meson distribution is slightly higher than charm spectrum at $\Delta\phi = \pi$, although the order of magnitude remains same. While at $\Delta\phi =$ 0, the situation is reversed. Similar observations are noted when figures at $p_T > 6.0$ GeV are compared. We feel that the above differences are caused by fragmentation function, D(z), which changes the p_T distribution of charm into p_T distribution of D mesons with, 0≤z≤1. Thus the correlation spectra of charm and D mesons may appear slightly different when we look into particular p_T regions. Finally it can be mentioned, D mesons rather than charms are observed in experiments. So calculating D meson correlation and comparing it with charm will give us deeper insights into the correlation study.

In Fig. 4, we have $E_c\, E_{\bar{c}} dN/d^3p_c\, d^3p_{\bar{c}}$ for charm average p_T of 2 GeV and 3 GeV. The figure shows change in azimuthal correlation of charm pairs with pairs at $\Delta\phi$=π

decreased considerably by inclusion of the energy loss mechanism.

To discuss our simple model of charm quark energy loss, we find that most of the charm pairs not only lose energy to shift to the lower momentum region but also back-to-back correlation for many charm pair is altered to almost collinear pairs. Also we find that two different energy loss mechanisms included in our study do not give much different outcomes. Further investigating at much higher momentum regions might bring out the differences between various energy loss mechanisms. The correlation study can be enriched if expanding medium is included in addition to energy loss by charms.

Next we move to our results for correlated decay of charm. In Fig. 5, we have $dN/dM_{e^+e^-}$ for di-electrons from correlated charm decay. We can recall that there is enhancement in D mesons as well single non-photonic electrons due to the effects of large drag on charm quark moving through QGP. Here we find a similar enhancement in di-electron spectrum at midrapidity. For $M_{e^+e^-}$ less than 1 GeV, there is increase in $dN/dM_{e^+e^-}$ by almost 12% which is quite noteworthy considering our model to be simple empirical mechanism of energy loss.

5. Summary

We have studied correlation of charm, D mesons as well as correlated decay of charm using NLO-pQCD processes and a simple empirical model for energy loss. The azimuthal correlations of charm show change when energy loss mechanisms are implemented along with cuts on charm transverse momentum. In case of di-electron distribution, energy loss enhances the electron spectrum slightly for low invariant mass.

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